POINCARÈ PLOTS AND SYMBOLIC DYNAMICS PATTERNS OF LEFT VENTRICULAR FUNCTION PARAMETERS EXTRACTED FROM ECHOCARDIOGRAPHIC ACOUSTIC QUANTIFICATION

G. D'Addio[1], E.G. Caiani[2], M. Turiel[3], S. Muzzupappa[3], A. Porta[3], S. Cerutti[2], F. Rengo[1]
[1]S. Maugeri Foundation, Rehabilitation Institute of Telese Terme, Italy
[2]Dipartimento di Bioingegneria, Politecnico di Milano, Milan, Italy
[3]Medicina Interna II and Dipartimento di Scienze Precliniche, Università degli Studi, Milan, Italy

Abstract-**Throughout the echocardiographic acoustic quantification technique, a non-invasive estimate of left ventricular volume (VV) is obtained and acquired in real-time. An automated algorithm is applied to extract the beat-by-beat values of ventricular function parameters.**

Their beat-by-beat variability has been recently studied, together with heart period (RR) variability, by spectral techniques. In this study, we propose to investigate this variability by nonlinear techniques, such as Poincarè plots (PPs) and symbolic dynamics (SyD) patterns.

A group of 17 normal young subjects (NY, 25±1 years) and a group of 12 normal old subjects (NO, 64±2 years) were studied to observe if this approach could be able to detect modifications in VV function connected with the ageing process.

Differences in RR, peak filling and peak ejection rate were evidenced by PPs indexes. SyD analysis evidenced different patterns: in RR a change from increasing/decreasing in NY to alternating pattern in NO was found, together with a change in SV pattern from random in NY to alternating in NO.

Consistent alternating patterns were found in VV derivative parameters. In conclusion, PPs and SyD patterns seemed able to evidence differences between NY and NO ventricular function, otherwise not captured by linear analysis techniques.

Keywords - **Left ventricular function, variability, symbolic dynamics, Poincarè plots.**

I. INTRODUCTION

The performance of the left ventricle is certainly one of the most important determinants of cardiovascular function and the assessment of its beat-by-beat variability can bear valuable information on some mechanisms inducing arterial pressure variability and, by reflex, part of heart period variability.

A continuous and non invasive measurement of ventricular volume (VV) has become accessible as analogic signal through the echocardiographic automatic endocardial border detection (Acoustic Quantification, AQ), based on differences in the blood and tissue intensities of the backscattered signal, and the consequent estimate of the instantaneous ventricular volume [1].

This VV signal has been first studied over the single (eventually averaged) cardiac cycle, thus obtaining non invasive measurements of ventricular function parameters. Recently, the difficulties inherent in keeping a reliable VV signal over few minutes and few hundreds of beats necessary to analyze VV variability have been faced and the first studies over this topic have been carried out [2, 3], assessing the VV variability by linear methods in time- and frequency-domains.

Since the VV variability is not fully described by linear techniques, aim of this study was 1) to investigate the beat-to-beat VV variability by quantitative indexes derived from Poincarè plots and symbolic dynamic patterns and 2) to observe if these parameters are able to detect modifications connected with the aging process in normal subjects.

II. SUBJECTS AND MEASUREMENTS

The study was performed on a population of 17 normal young subjects (NY-age 25±1 years) and 12 normal old subjects (NO-age 64±2years) examined by an experienced sonographer during spontaneous breathing over a mean period of 4 minutes.

All subjects were included on the basis of the following criteria: 1) no history or evidence of cardiovascular, pulmonary or systemic disease; 2) no pharmacological therapy; 3) normal sinus rhythm; 4) normal 2D and colour-Doppler echocardiographic study, according to age and sex.

Cardiac imaging in apical four-chamber view was performed using a commercial ultrasound imaging system (Sonos 2500, Agilent Technologies, Andover, MA), equipped with AQ software and output data port.

A transthoracic 2.5MHz transducer was used. Gain controls were adjusted to optimize endocardial border detection and to track at least 70% of the endocardial border within a predefined region of interest throughout the cardiac cycle. The VV signal was obtained in real time by using the disc model available in the imaging system and recorded from the relevant analogue output port.

ECG, respiration (with a piezoelectric thoracic belt) and VV signals were A/D converted (DT300, Data Translation, Marlboro, MA) at 300 Hz sampling rate, 12 bit precision, on a PC.

To reduce broad band noise, VV signal was low-pass filtered (15Hz cut-off frequency, 150 coefficients FIR filter).

III. BEAT-BY-BEAT VARIABILITY SERIES

Signals were automatically processed to extract beat-by-beat variability series as follows [2,4].

The R peaks of the ECG were detected via a classical derivative threshold algorithm, thus obtaining the series of RR(i) interval durations (i=1,...N; N number of beats).

The i-th end diastolic volume, EDV(i), was searched as the maximum of VV found starting from the beginning of interval RR(i). The corresponding end systolic volume, ESV(i), was found as the following minimum. Stroke volume, SV(i), was computed as EDV(i)-ESV(i). On LV volume derivative, obtained by a derivative FIR filter (15 Hz cut-off frequency, 150 coefficients), the search for the peak filling rate PF(i), peak atrial filling rate PA(i) and peak ejection rate PE(i) was based on the EDV and ESV detected points (figure 1).

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
25 Oct 2001	N/A	-

Title and Subtitle Poincare Plots and Symbolic Dynamics Patterns of Left Ventricular Function Parameters Extracted From Echocardiographic Acoustic Quantification	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) S. Maugeri Foundation Rehabilitation Institute of Telese Terme, Italy	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) US Army Research, Development & Standardization Group (UK) PSC 802 Box 15 FPO AE 09499-1500	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)
Distribution/Availability Statement Approved for public release, distribution unlimited	
Supplementary Notes Papers from 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, October 25-28, 2001, held in Istanbul, Turkey. See also ADM001351 for entire conference on cd-rom.	
Abstract	
Subject Terms	
Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU
Number of Pages 4	

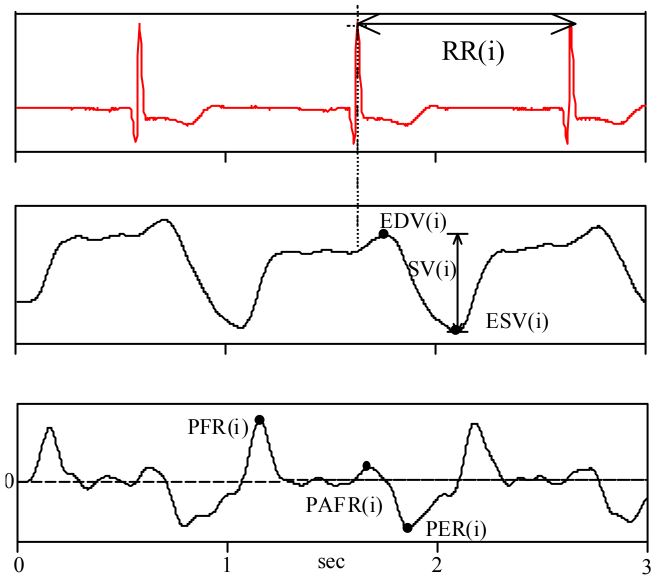

Figure 1. ECG, VV signal and its first derivative (from top to bottom), with fiducial points used to extract beat-by-beat variability series (modified tracing by [2]).

IV. POINCARE' PLOTS ANALYSIS

Poincarè plot analysis is a simple and robust graphical technique based on the analysis of the maps obtained by plotting each sample against the preceding one.

This analysis doesn't require time-closed couples nor a normal distribution or stationarity, like in linear time- or frequency-domain analysis. For these reasons, it can be particularly useful to extract relevant information on beat-to-beat signal dynamics, especially during short-term and non-stationary condition. To overcome the limitation of subjective evaluation of the plots, our group has recently introduced new signal processing procedures to automatically quantify their major morphological characteristics [5-7].

In this study, focusing on short-term analysis, only bidimensional plots were considered and the parameters computed were the extension and dispersion of the ellipsoidal cloud of points around the bisecting line, namely the length (L) the area (A) and the highest variability extension (HVE).

The latter can be obtained scanning the plot with a vertical line and generating a curve which represent the measure of scatterplot width at different values (figure 2).

This curve can be numerically quantified by the highest variability (HVE index) and the related time series sample (HVE§).

V. SYMBOLIC DYNAMICS ANALYSIS

Symbolic dynamics analysis was performed transforming the original time series into symbol sequences from a given alphabet [8].

For our short-term recordings, we found adequate to use lenght-2 words of a minimum alphabet {+,–}, based on the sign of the differences between values of studied parameters corresponding to three adjacent beats.

These length-2 words represent very short-term patterns of decreasing (–,–), increasing (+,+) or alternating (+,– or –,+) sequences that can be easily displayed in a four-quadrant plot.

To avoid differences in the statistical properties, the analysis was performed on records containing the same number of values extracted from 200 consecutive beats.

The statistical significance of this four words distribution was evaluated by first testing the null hypothesis of equally occupancy in each quadrant using a chi-square test, and then performing subsequent chi-square tests to classify the quadrant predominance.

These four-quadrant plots remove the dominant characteristic appearing in the Poincarè plots, i.e. the correlation between one interval and the next, splitting the single cloud of point of the Poincarè plot in four small clouds.

Differently from the previous application for long-term analysis of RR series [9,10], we propose also to quantify these clouds of points by the distance of their center of mass (Bx) from the origin, which represent the amount of variation of the predominant pattern (figure 3).

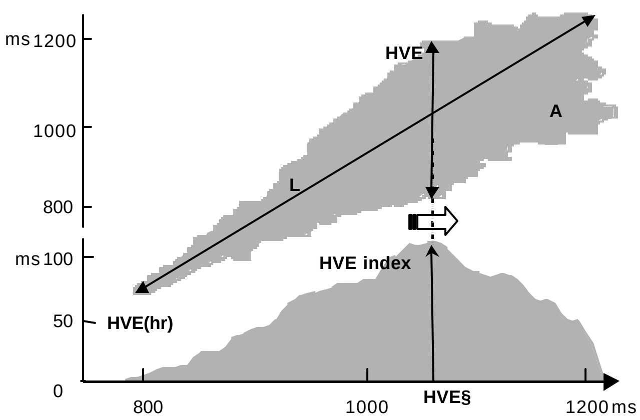

Figure 2. 2D Poincarè plots parameters, see text for details.

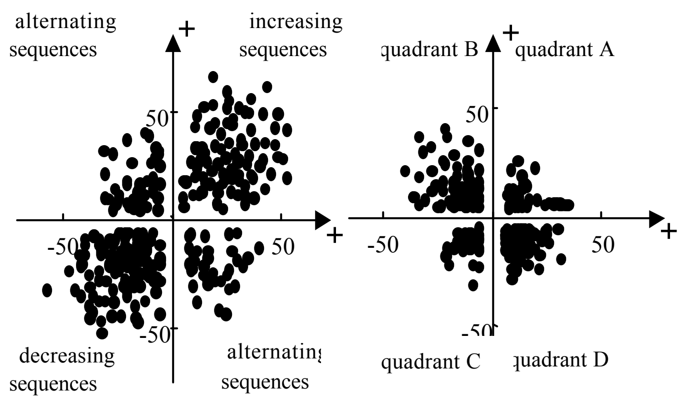

Figure 3. Four-quadrant plots. Example of RR patterns in NY (left) and NO (right), see text for details.

VI. RESULTS

Summary results of time-domain and Poincarè plot parameters are showed in table 1. To test the statistical difference between NY and NO, an unpaired Student t-test was applied, with $p<0.05$ considered significant.

TABLE I

RR	Mean	Variance	L	HVE	HVE§	A
NY	859±34	2575±622	184±18	81±9	857±49	648±105
NO	895±36	410±87*	133±14*	48±6*	896±36	490±79
SV						
NY	45±3	49±10	30±4	15±2	47±3	58±12
NO	42±4	29±7	25±3	13±2	44±4	60±10
PA						
NY	121±9	1017±121	129±9	63±7	140±13	458±86
NO	150±12*	1101±220	128±9	69±3	150±9	566±42
PE						
NY	271±19	1615±369	156±7	87±9	276±25	771±90
NO	211±23*	829±168	134±9	78±5	211±22*	650±49
PF						
NY	297±20	2533±507	205±20	92±11	314±28	598±130
NO	223±28*	2209±712	139±9*	80±6	222±29*	625±77

Mean ± st. error (*:p<0.05)

For RR series, HVE§ and A were unchanged, while the variance, L and HVE decreased in NO.

Regarding the VV variability series, similar values of HVE§ in SV were observed in both populations, while significant differences were found in peak filling (PF) and peak ejection (PE), with a reduction in NO: In peak atrial (PA) an increasing trend, hence not significant, was observed in NO. The extension of the cloud of points (L) showed in PF a significant decrease in NO, while no differences were evidenced for the other parameters. Also the area of the clouds (A) was not able to evidence significant differences between NY and NO.

The symbolic dynamics patterns showed a significant tendency toward non-random distribution for all parameters except SV in NY (chi-square, $p < 0.05$), in which was impossible to observe a clear predominance of one quadrant on the others.

Superimposing the dominant quadrants of all non-random patterns, we obtained an average quadrant occupancy (figure 4) for each variable which showed :

1) for RR series a predominance of accelerated and decelerated sequences (+/+ and -/-, quadrants a and c) in NY, with a pattern inversion and a significant contraction in NO (barycentre Bx=51 vs 23, respectively);
2) for SV series a predominance of alternating sequences (+/- and -/+, quadrants b and d) in NO vs a random distribution in NY;
3) for PA series the same predominance of alternating sequences both in NY and NO;
4) for PE series the same predominance of alternating sequences in both populations but with a significant pattern contraction in NO (Bx=58 vs 32);
5) for PF series the same predominance of alternating sequences in both populations but with a significant pattern contraction (Bx=97 vs 64).

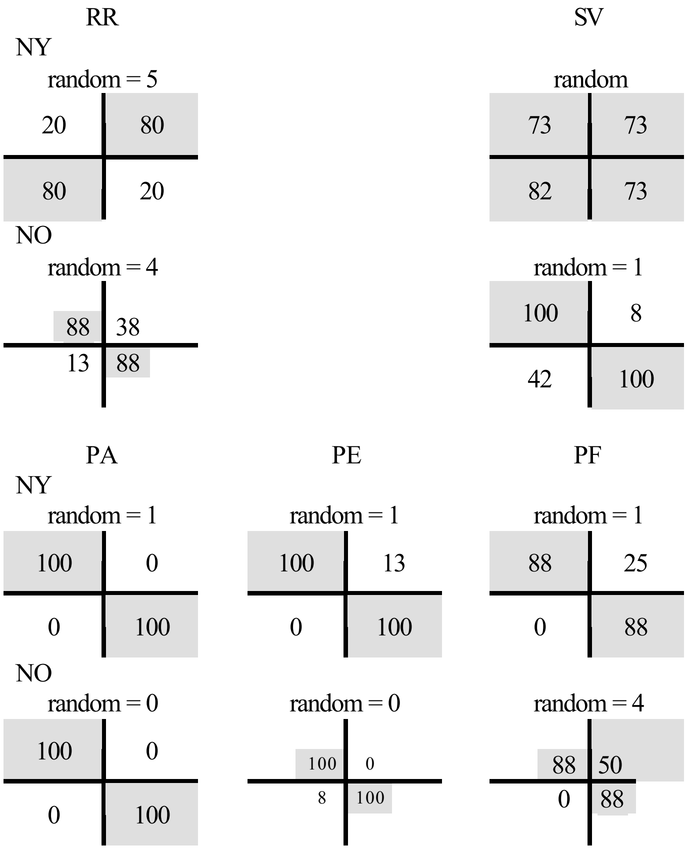

Figure 4. In gray, the average dominant quadrants in NY and NO for all parameters. For each four-quadrant plot, it's shown the number of random patterns and each quadrant predominance probability (%).

VII. DISCUSSION

We proceeded to investigate the beat-to-beat variability of heart rate and left ventricular parameters by quantitative indexes derived from Poincarè plots and symbolic dynamic patterns, to verify if these new indexes could be able to observe modifications connected with the aging process.

The expected reduction in heart rate variability in older subjects was indeed reflected by the parameters L and HVE, representing respectively the horizontal and vertical maximum extension of the cloud of points.

We found the parameter HVE§ reflecting the value around whom the majority of points were concentrated. As supposed by the physiological modifications due to the aging process, the HVE§ in peak filling rate was found decreased in normal older subjects.

In fact, the reduction of myocites and the presence of fibrotic tissue produces an increase in the relaxation time and a smaller peak filling and, as a consequence, a lower ventricular filling in presence of an unchanged RR interval [2,11]. This produces a more concentrated cloud of PF values along the horizontal dimension, as evidenced by the value of L, representing the extension of the cloud, found reduced in older subjects.

The reduction of HVE§ in peak ejection rate, found in NO, could be explained both by the increase of systolic arterial pressure relevant to the ageing process, connected with a greater aortic impedance and peripheral resistances, and by the prolongation of the contraction time, related to age-induced tissue changes [2]. Hence not significant (p=0.08), the value of L was reduced in NO too, evidencing a cloud less expanded in the horizontal dimension than in NY.

On the contrary, no difference in HVE§ was found in SV: in fact, the aging process in a normal subject involves an increase of mass and wall thickness of LV, but does not induce a change in ventricular dimensions [12,13].

The symbolic dynamics approach showed an interesting peculiar behavior, revealing different pattern in interval sequencing and marking state-dependent differences in the control of cardiac variability not detectable in frequency-domain, in which sudden beat-to-beat changes could appear just as wideband noise.

The reduction in heart rate variability observed in NO was accompanied by a pattern inversion: from accelerating and decelerating pattern in NY to an alternating one in NO. Comparing these results to those previously obtained [14] in a different group of normal subjects (mean age 59, L=213, HVE=78; dominant probability: alternating = 33%, accelerating = 56%, decelerating = 78%), we can observe that a progressive reduction of heart rate variability, related to the age of the examined group, seems to generate a progressive change in the pattern towards the alternating one in older subjects. Additionally, a simultaneous reduction of the extension of changes was evidenced by a decrease in the center of mass position.

In SV, the clear prevalence of alternating sequences in NO could be explained both by the reduction of variability, hence not significant (p=0.07), observed in the series of this parameter, and by a less modulation of VV induced by respiration [2].

The consistent non-random and alternating patterns found in VV derivative parameters in both groups could be interpreted as due to the more noisy nature of these variability series. However, sequence analysis showed in NO a contraction of the patterns toward the origin for PE and PF, probably reflecting the reduction in the amplitude of the beat-to-beat changes, related to the increased ventricular stiffness and to the reduced capacity of the heart in adapting to preload and afterload pressure changes [15,16].

These findings confirmed that the analysis of beat-to beat variability of VV parameters could add further information in a non-invasive study of left ventricular function.

The analysis of Poincarè plot indexes allowed to detect differences between normal young and older subjects in the VV parameters.

Although we are aware of the need of further investigations to disclose the connections between symbolic dynamics patterns and physiologic events, our results led us to conclude that valuable information may be gained from VV time series using the symbolic dynamic approach.

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